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Design and simulation of integrated intelligent control system of front wheel active steering and Direct Yaw moment Control by Electric motors help to improve vehicle stability on dry roads steering maneuver

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ABSTRACT
In this paper, an integrated intelligent control system for front wheel active steering and direct Yaw moment control is designed in which the direct Yaw moment is located through two Brushless DC electric motor (BLDC) allocated to the rear wheels.The integrated intelligent control system is designed in two layers; top layer controller *using a sliding mode control and a combined sliding surface, with rotational angular velocity and vehicle desired actual side slip angle as controller input determines the front wheels steering wheel correction angle and required Yaw moment to pursue more desirable values. Optimal values of the rotational angular velocity and the vehicle side slip angle for the top layer controller are obtained using the steady state response of nonlinear four-DOF model, as a two-dimensional function of the longitudinal speed and steering wheel angle. Control inputs from the top layer controller are sent to the bottom layer controllers including active steering system electric motor control, wheel slip controller and electric motor torque to be applied to the vehicle. Simulation results using nine degrees of freedom nonlinear model of the vehicle and magic tire model shows dry road steering maneuver; that integrated control system designed in this paper has the ability to maintain stability and pursue optimal values of rotational angular velocity and side slip angle of the vehicle in terms of all motion road conditions, and the control system is also resistant to change in the parameters of the vehicle and road friction estimation error.*
***Keywords**: Integrated intelligent controller, Direct Yaw moment Control, Front wheels active steering, Sliding mode control, Electric motor*

INTRODUCTION

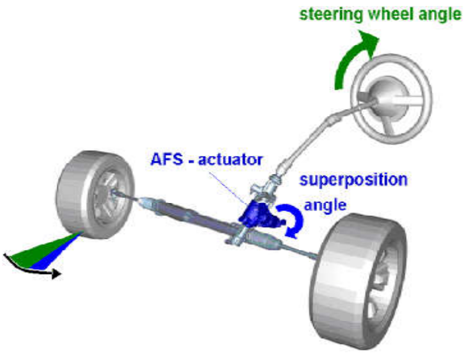
Nowadays, a large amount of research and developments in the automotive industry occurs in order to maintain stability and improved vehicle handling in critical condition. In automotive engineering, the term active safety is commonly referred to systems automatically reduces the likelihood of accident. These systems help the driver to more control the car by controlling longitudinal or lateral dynamics. Active safety systems that control the lateral dynamics of car to maintain vehicle stability on automobile handling under conditions such as sudden handling and or car movement on slippery road. Direct Yaw moment Control (DYC) and Active Steering Control (ASC) is among the effective methods in controlling lateral dynamics of the vehicle, so researchers have paid a lot of to this issue in recent years. These systems creating longitudinal and lateral forces on the tires control the Yaw moment and thus the rotational angular velocity and side slip angle of the vehicle. Hence, these systems are generally called Yaw Stability Control systems (YSC). ASC and DYC systems have the maximum efficacy in a specified range of tire performance, so using an integrated control system that uses optimized both of these systems to improve system performance and maintain stability and automobile handling is useful in all cases.

ACTIVE STEERING SYSTEM

Since in most cars, the steering mechanism is on the front wheels and active rear wheels steering and four-wheel require a steering mechanism on the rear wheels; and according to research done in this field it has been proven that front wheels active steering is more effective and economical than other steering systems. In this system, front wheels steering angle is controlled dynamically in regard to driver input angle and lateral dynamics of vehicle. Several methods are used to control front wheels steering angle. Active steering with solar gear system is one of the methods to control steering angle. The system schematic of Figure (1) shows a controlled superposition angle through an electric actuator applied on steering wheel. This added degree of freedom enables steering wheel to adapt its conditions depending on driving properties and characteristics such as convenience and optimized steering wheel as well as steering wheel interference in vehicle stabilization [1].

Direct Yaw moment Control Using an Electric Motor

Direct Yaw moment Control (DYC) is another active safety system that controls the Yaw moment and thus the car's stability and automobile handling crating a longitudinal force on the tires. Stability and automobile handling of electric vehicles have also been researched with the development of research on (EVs). In these vehicles, the Yaw moment can be created controlling drive and braking torque control of electric motors in the wheels of the vehicle [2] and [3] and [4]. These electric motors, as shown in Figure 2, are located in rear wheels in front wheel drive vehicles and provide required Yaw moment by making the equal and opposite driving and braking forces. In this way, the equal and opposite longitudinal forces generated in the left and right wheels do not affect the vehicle longitudinal dynamics [6].



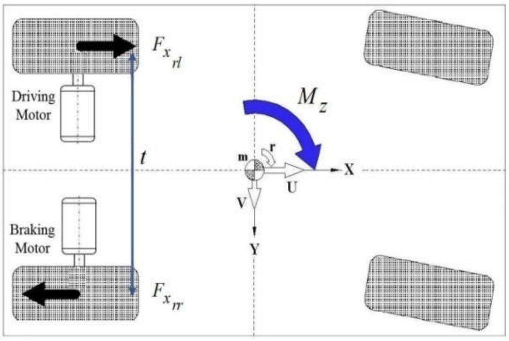


Figure 1 Front wheels active steering system by total spin solar gear
Figure 2 Direct Yaw moment by the electric motors on the rear wheels

Vehicle Dynamics Integrated Control

As mentioned in the previous section, active steering and Direct Yaw moment Control systems are effective methods used in vehicle stability control and automobile handling. Meanwhile, each of which showing the best performance under certain conditions. As Figure (3) shows, the transverse profile of the tire slip angle of the vehicle according to different road conditions (different friction coefficients), has three parts: linear, nonlinear and saturated**.**

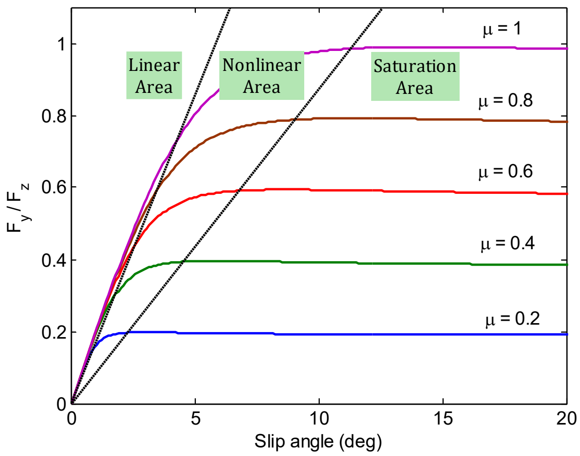


Figure 3 Linear, nonlinear and saturated areas of lateral force on the tire slip angle

Each of the two systems shows more vehicle control effect in the range of motion of the vehicle and road conditions, due to the nonlinear behavior of the tire and various road conditions. For example, active steering control system in the linear range of the tire is able to control the vehicle stability and DYC system is also effective when the vehicle is in the range of nonlinear motion and steering the wheels is not effective due to saturation of lateral force to tires. Thus, the integrated control of both systems can solve this problem and improve the dynamic behavior of maneuvering a vehicle on the road.

Vehicle dynamics and electric motor modeling

Vehicle dynamics control requires mathematical modeling of the dynamic behavior.The study aims to investigate the lateral dynamics and good steering parameters of the vehicle using the eight degree of freedom with a one degree of freedom sub model of the steering mechanism and combined slip nonlinear tire model.

Vehicle dynamics comprehensive model

Modeling is required to simulate the movement of the vehicle. Hence it is necessary for a model to show the main characteristics of the vehicle motion. In this research, a comprehensive nonlinear model with degrees of freedom of the longitudinal velocity (u), lateral velocity (v), Yaw angular velocity (r), sprung mass roll angle (ϕ), four degrees of freedom related to the rotational speed of each wheel (ω_i), front wheel steering angle(δ_f), were used for the simulation of vehicle dynamics. Figure 4 shows Schematic model of nine degrees of freedom, coordinate axes and the forces acting on the vehicle.

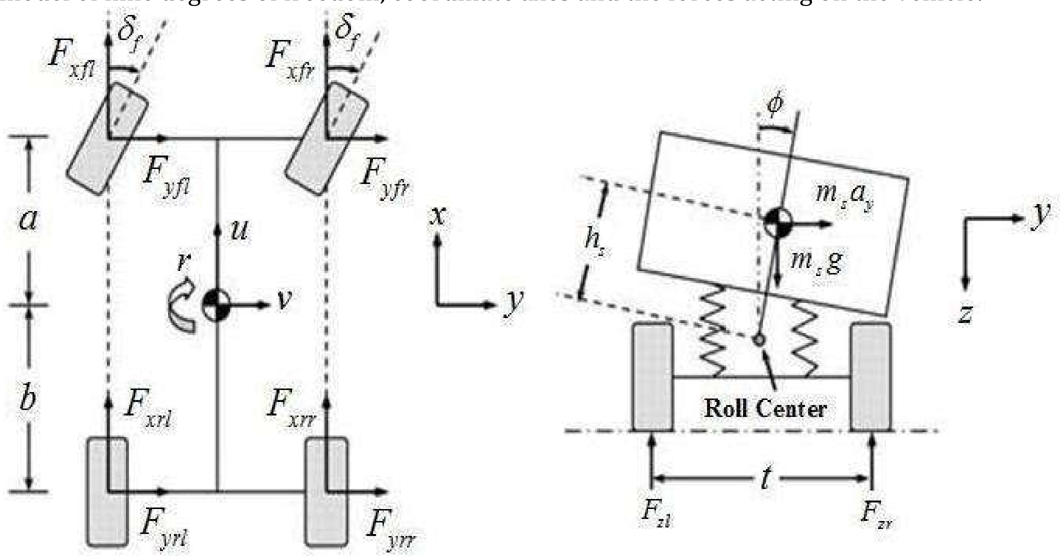
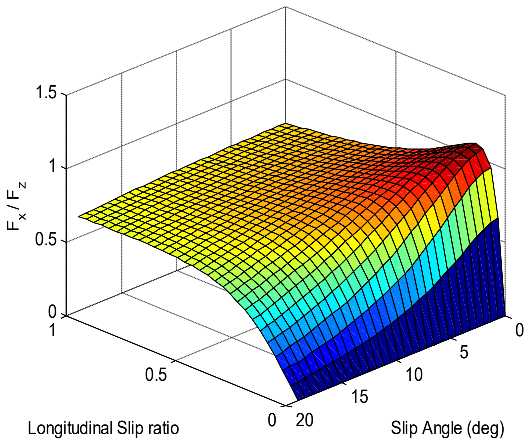


Figure 4 Vehicle nine degrees of freedom model

Tire model

To solve vehicle model differential equations a model required to obtain longitudinal, transverse and collimator tire torque. The non-linear models are more accurate and useful than linear models. [7] Magic Formula (MF) tire model known as 2002Pacejka tire is a tire nonlinear model more used on vehicle dynamics simulation. This model is largely experimental in nature and is composed of a set of mathematical functions partly based on the physical properties of the tire; thus it is called tire semi-empirical model [8].

Magic Formula tire model calculates longitudinal, transverse and collimator tire torque forces in both pure and hybrid slip using longitudinal slip ratio, slip angle, Camber angle and tire vertical angle as input. Combined tire slip model is among the best models in the simulation of nonlinear dynamic steering stability of a vehicle. This model considers longitudinal slip effect on tire transverse force production and lateral slip angular effect on tire longitudinal slip force production. The reason behind the use of combined slid model is to enforce limitations on tire force production when longitudinal and lateral forces of tire are produced simultaneously. Two-dimensional surface longitudinal and transverse forces of tire in terms, longitudinal slip and lateral angular slip are shown in Figures (5) and (6).



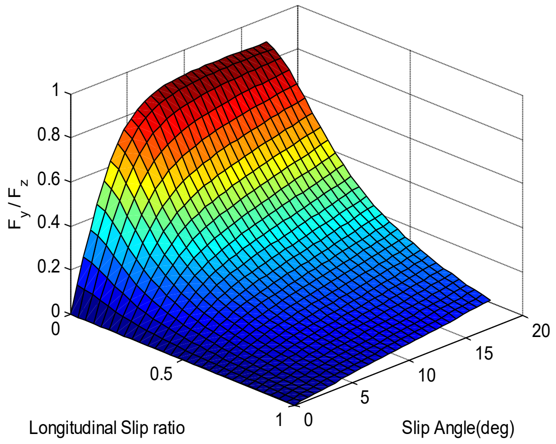


Figure 5 Normalized longitudinal force diagram in terms of the lateral slip angle and longitudinal slip

Figure 6 Normalized transverse force diagram in terms of the lateral slip angle and longitudinal slip

Lateral tire forces time delay

This section considers the effect of tire transverse force time delays on the lateral dynamics of the vehicle as an important aspect of the tire modeling. The tire in the creation of lateral force shows time delays, i.e. By giving angle of the steering wheel, tire lateral force will not be made immediately, but with a time delays. The role of lateral tire force time delays vehicle lateral dynamics in high velocity and transient state maneuvering is remarkable. In this paper this effect is modeled as a first order time delay function [5]:

$$\tau \dot{F}_{yw} + F_{yw} = F_{ywss} \qquad (1)$$

Where, F_{ywss} is tire lateral force at steady state. τ is time constant of differential equation (1) calculates as:

$$\tau = \frac{RL_y}{u} \qquad (2)$$

Where, RL_y is Lateral relaxation length.

Electric motor model

Brushless DC motors (BLDC) are a set of permanent magnet synchronous motors (PMSM) with a magnet rotor and windings on the stator. Electric motor studied in this paper has three-phase star connected windings on the stator and four magnetic pole pairs on the rotor.

A three-phase BLDC motor real model requires much time and powerful processor for simulation, so this paper uses a simplified model of a single-phase electric motor. Assuming that the three-phase inverter is able to create a perfect harmony between the electric current in each phase and each phase induction electric power and also, regardless of the dynamics of the inverter a single-phase simplified BLDC motor model can be used. Equivalent circuit is shown in Figure (7).

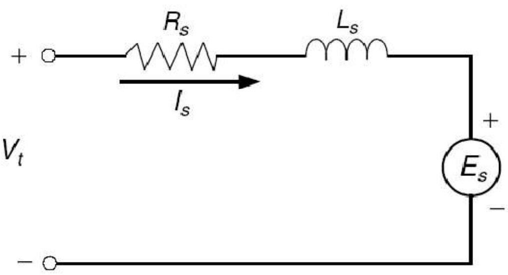


Figure 7 A single-phase electric BLDC model equivalent circuit [9]

The controller design

In this paper, an integrated intelligent control system for front wheel active steering and direct Yaw moment control is designed in which the direct Yaw moment is located through two Brushless DC electric motor (BLDC) allocated to the rear wheels .Because the task of the controller is minimizing the difference between the system response and the optimum response, thus, an important part of the design of the controller is to determine desired response for the system. The integrated intelligent control system is designed in two layers; top layer *controller* using a rotational angular velocity and actual and optimum slip lateral angle that determine correcting the steering angle and Yaw moment for the optimum values. Control inputs from the top layer controller are sent to the bottom layer controllers including active steering system electric motor control, wheel slip controller and electric motor torque to be applied to the vehicle. These controllers, by exerted torque on the electric motors in the rear layout produce longitudinal slips, resulting in the desired longitudinal forces on the rear wheels; the longitudinal forces in the desired Yaw moment obtained from the top layer create the top layer controller. For robust integrated controller to changes in the parameters of the vehicle and road conditions, slip sliding mode control method to design top layer controller and wheel slip controller.

To create the desired values

Because the task of the controller is minimizing the difference between the system response and the optimum response, thus the first step in the design of vehicle dynamics controller is to define the desired motion of the vehicle. Two variables of lateral mechanics i.e. yaw angular velocity and lateral velocity is used to define desired motion. So that in a dynamic maneuver, the yaw angular velocity and lateral velocity of the vehicle must be close to the optimal values. Usually, in the study of vehicle dynamics, sideslip angle is used in place of lateral velocity of the vehicle. The lateral sideslip angle is actually the angle between the velocities of the center of mass of the vehicle with tangent line on the direction of motion. The vehicle Yaw angular velocity on bypass with constant speed in a steady state is indicating the turning radius of the vehicle, so that the higher angular velocity, the smaller the radius of the path. In fact, the following equation is between the vehicle motion path radius in the steady state and angular velocity of the rotation of vehicles:

$$r = \frac{U}{R} \qquad (3)$$

In the above equation, R is motion path radius; U longitudinal velocity of the vehicle on turning in steady state.

Nonlinear model of the vehicle shall be used to obtain a desired response in the all vehicle lateral velocities. For this purpose, this paper uses a four degree of freedom of vehicle is used with a nonlinear tire model. Solving roll, lateral and steering dynamic equations in the steady state and nonlinear tire model, for input longitudinal velocity and steering wheel angle, values of the yaw angular velocity and side slip angle of the vehicle in steady state are obtained as a two variable function in terms of the longitudinal velocity and steering wheel angle. Figure (8) depicts a two-dimensional yaw angular velocity procedure and Figure (9) depicts desired side slip angle of the vehicle in terms of velocity and steering wheel angle. The diagrams for the vehicle used in this study were estimated assuming a dry road $(\mu = 0.9)$ travel.

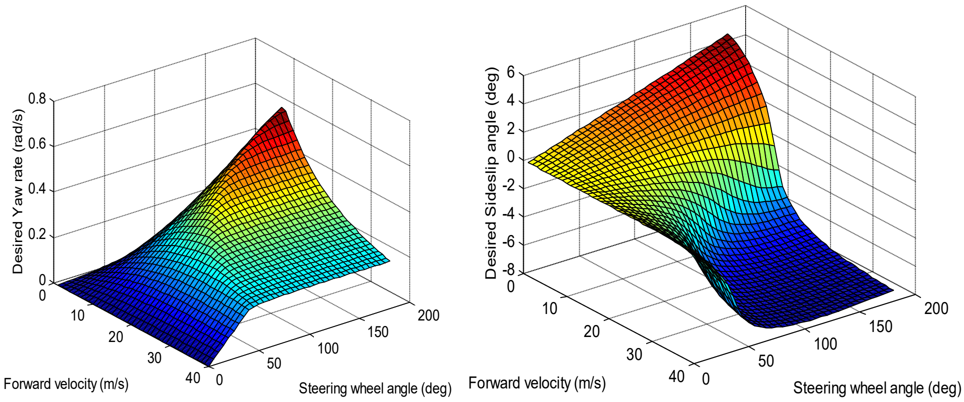


Figure 8 Two-dimensional yaw angular velocity procedures

Figure 9 Two-dimensional side slip angle of the vehicle in terms of longitudinal velocity and desired angle in terms of longitudinal velocity and steering wheel on a dry road

Top layer controller design

The integrated controller proposed in this study is composed of two levels of control. As shown in Figure (10), on the first level, a sliding mode controller receives a command from the driver, and considering the environmental data and calculating the optimum values, calculates the required values of steering angle correction and yaw torque commands that will be performed by the second level controller. For the robustness of the controller to changes in the system parameters and the uncertainty in the vehicle lateral dynamics equation, sliding mode control method is used in the controller design.

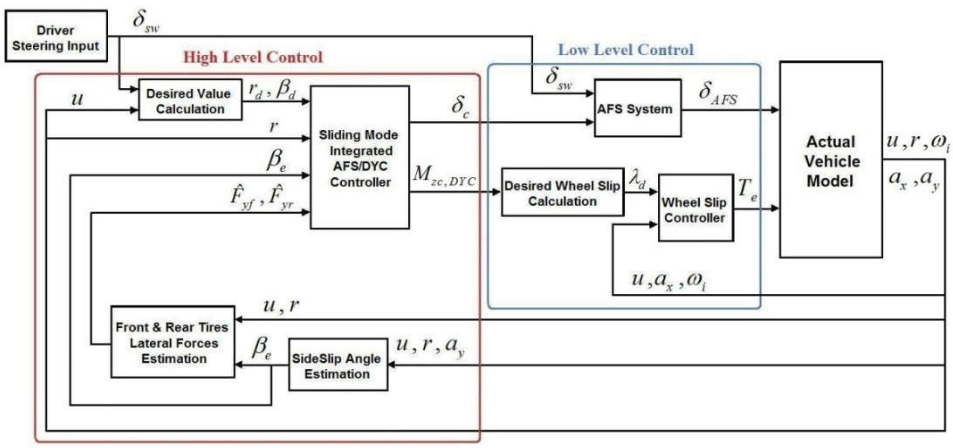


Figure 10 Block diagram of the control system proposed in this study

Two lateral dynamic variables i.e. yaw angular velocity and lateral slip angle of vehicle must be controlled to control automobile handling and lateral stability, so that the real value of these variables can be close to the optimal values obtained in the previous section. However, according to researchers conducted in this study, side slip angle converges to the exact desired values in the integrated active steering Yaw moment Control causes of excessive steering correction angle and creates contrary Yaw moment outputs in both the front steering system and Yaw moment, thus, both systems operate conversely. Therefore, the simultaneous control of Yaw moment angular velocity and side slip angle of the vehicle may not be accurate.

Based on the above discussion, the arguments used in the design of the controller is that because the yaw moment angular velocity of the vehicle is in direct relationship with automobile handling and track keeping, its increase and decrease respectively increases and decreases sensitivity to the values of input steering wheel angle and both are undesirable in terms of automobile handling and maintaining the correct path of the vehicle.

In other words, it is necessary to deliver the yaw moment angular velocity to desired value. However, regarding the side slip angle of the vehicle the lower absolute value than the values presented in the previous section is not only does not create a problem in vehicle stability, but if there is no error in the controller output, improves lateral stability of vehicles automobile handling and lateral stability of the vehicle is reduced. Thus, in the he solution proposed in this research to design a controller, to converge yaw moment angular velocity of the vehicle to the desired values and Keep the vehicle side slip angle in smaller or equal to the desired value is optimal.

M_{zc} the total yaw moment torque stabilizer applied to the vehicle by DYC and AFS systems is obtained by the following equation

$$M_{zc} = M_{zc,DYC} + M_{zc,AFS} \qquad (4)$$

Where, in equation (4), $M_{zc,AFS}$ and $M_{zc,DYC}$ are yaw moment torque stabilizer applied to the vehicle by AFS and DYC systems, respectively. After determining the correct steering angle and direct Yaw moment of top layer DYC and AFS, the control inputs are sent to the lower layer controllers. The controllers design will be conducted in the following manner.

The bottom layer controller design

Since the control inputs from the upper layer controller are direct Yaw moment and front steering wheels correction angle; bottom layer controllers should be used to implement the control inputs to the vehicle. Steering wheels correction angle is applied to the vehicle using AFS system electric motor control. Steering wheels correction angle is obtained from top layer controller. Steering angle correction is in front wheels, but AFS steering system used in this study, steering angle correction is located on steering wheel using a solar gear system; So the steering angle correction that is added to AFS system electric motor as a angular point of reference is obtained by the following equation:

$$\delta_{c,sw} = N_g \delta_c \qquad (5)$$

As a result, the steering angle applied to the vehicle through the AFS system is obtained as follows:

$$\delta_{AFS} = \delta_{sw} + \delta_{c,sw} \qquad (6)$$

In addition, the direct Yaw moment applied to the vehicle should be transformed into longitudinal force to the wheels that these longitudinal forces are created by applying electric motors torque and or a brakes system in the wheels. In this study, corrective Yaw moment that is created by two BLDC electric motors located at the rear wheels. Equal and opposite driving and braking forces are created on either side of the vehicle. Since these two forces act as a coupling force, rear longitudinal forces are calculated from the following relationship:

$$F_{xrl} = \frac{M_{zc,DYC}}{t} \quad , \quad F_{xrr} = -\frac{M_{zc,DYC}}{t} \qquad (7)$$

Because the longitudinal tire force is a function of the longitudinal slip, to create a desired longitudinal force on the wheel, longitudinal wheel slip must be controlled. This is done by wheel slip controller.

The task of the controller is to control rear wheel slip by setting the reference torque suitable for electric motors, so that the electric motors provide the desired longitudinal force through a longitudinal slid in the rear wheels, and thus create the calculated Yaw moment by top layer on the vehicle. In addition, motor torque must be controlled to apply the reference torque by electric motor. This is done through electric motors torque controller using stator current control.

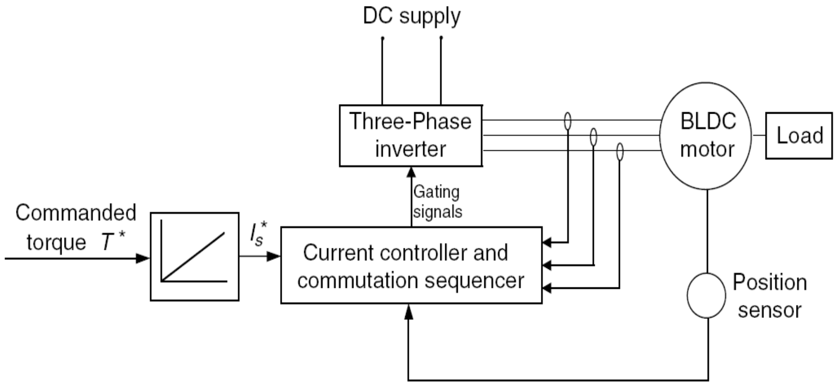
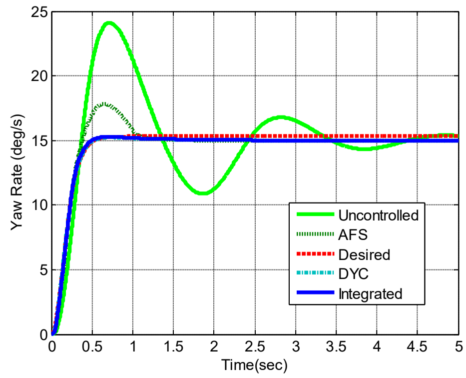


Figure 11 Block diagram of the three-phase BLDC electric motor torque control

Controller simulation at constant input maneuvering on dry roads Simulation results of this section includes diagrams of the yaw moment angular velocity (r), the side slip angle (β) and lateral acceleration of the vehicle (a_y) plus the reference Yaw moment created by $(M_{zc,DYC})$ electric motors in both DYC and integrated controllers modes, steering angle correction on the steering wheel $(\delta_{c,sw})$ in both AFS and integrated controller, reference torque and applied torque on the rear wheels via an electric motor, left and right electric motors input voltage, and vehicle path diagrams.

In this section, simulating the movement of vehicles in states without controller, with integrated controller and separated DYC and AFS controllers, in constant linear velocity of 30 meters per second at a constant 90 ° steering wheel angle is performed on dry roads $(\mu = 0.9)$. The results of the simulation are shown in Figures (12) to (21).



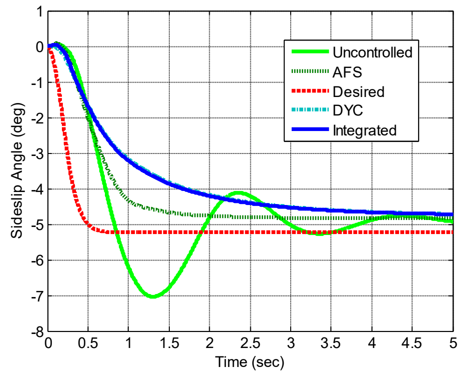
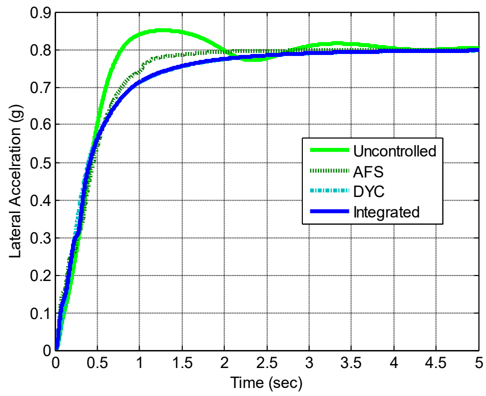


Figure (12) Rotational angular velocity of the maneuver on dry roads
Figure (13) Side slip angle of the fixed steering maneuver on dry roads



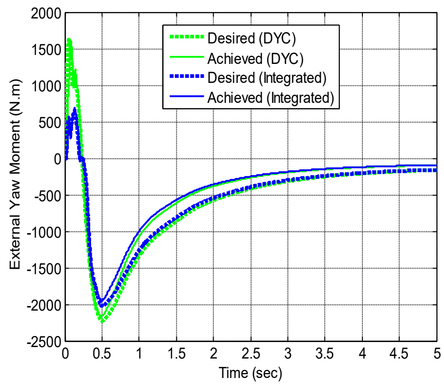
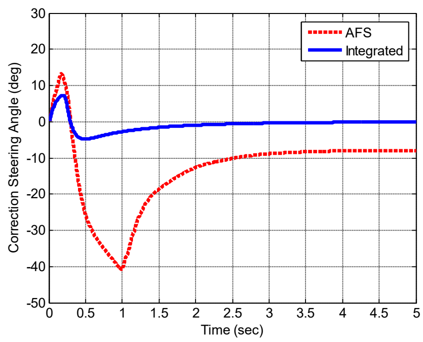


Figure (14) Lateral acceleration on maneuvers on dry roads

Figure (15) Reference rotational torque applied to the fixed steering vehicle on dry roads



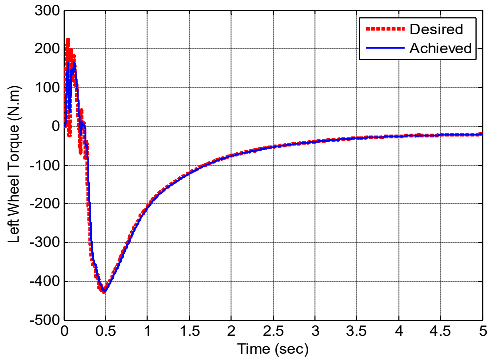
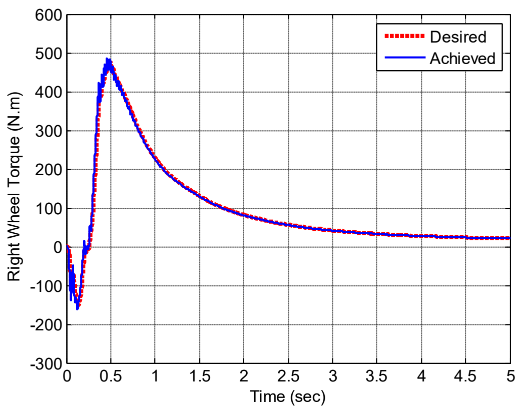


Figure (16) Steering correction angles of the front wheels of the fixed steering maneuver on dry roads

Figure (17) Reference and applied torque to the left rear wheel of the fixed steering maneuver on dry roads



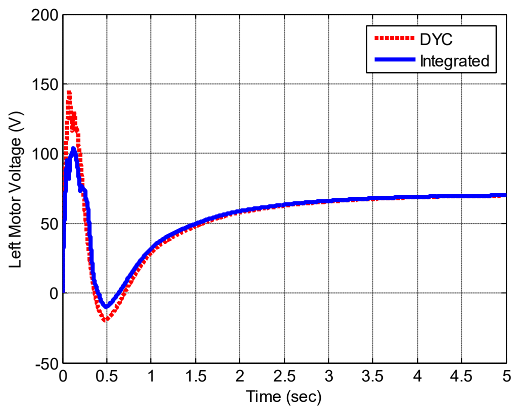
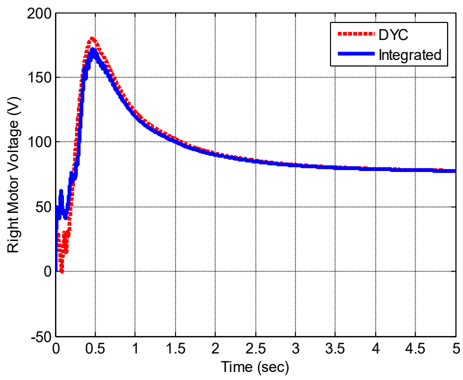


Figure (18) Reference and applied torque to the right rear wheel of the fixed steering maneuver on dry roads

Figure (19) Electric motor input voltage to the left of the fixed steering maneuver on dry roads



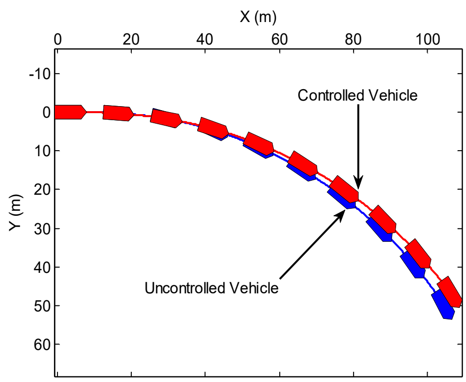


Figure (20) Electric motor input voltage to the right of the fixed steering maneuver on dry roads

Figure (21) The movement of the vehicle at a constant steering maneuver on dry roads

CONCLUSION

Based on the simulations performed, it is concluded that the integrated control system designed in this paper has the ability to maintain stability and pursue optimal values of yaw moment angular velocity of the vehicle and side slip angle, respectively. Moreover, the simulation results show that the proposed combined top layer sliding mode controller in this paper has a good performance to pursue yaw moment angular velocity values and maintain side slip angle in smaller or equal to optimal values. Therefore, the choice of control method for simultaneously controlling the yaw moment angular velocity and side slip angle of the vehicle, the problem with simultaneous control of two state variables using a sliding surface, have been met**.**

Also, compared the performance of the integrated control system with DYC and AFS systems designed in this paper, it is observed that AFS steering system performance reduced severely at high velocity maneuvers, despite the fact that DYC system can control the lateral dynamics of the vehicle in all lateral velocities. However, due to the large control inputs for Yaw moment stabilizer, the electric motors power is more than integrated control system. Moreover, the control inputs in integrated controller system (Yaw moment and steering angle correction) is smaller than that of AFS and DYC systems and this means the optimal control inputs of integrated control system than that of separated AFS and DYC systems.

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